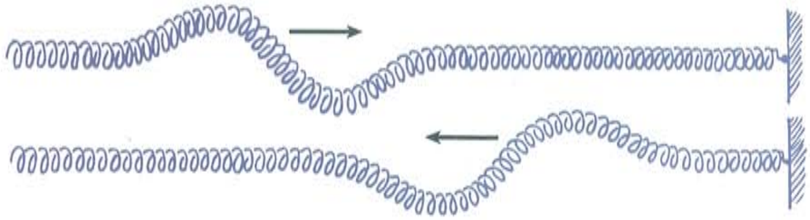
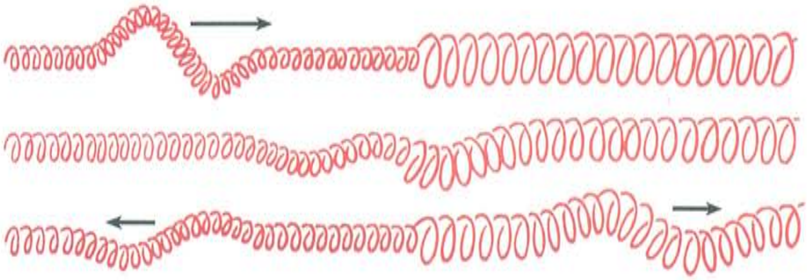


Figure 29.1 ▲
A wave is totally reflected when it reaches a completely rigid boundary.

the new medium. Some of the wave energy is still reflected. These waves are *partially reflected.*

A metal surface is rigid to light waves that shine upon it. Light energy does not propagate into the metal, and instead is returned in a reflected wave. The wave reflected from a metal surface has almost the full intensity of the incoming wave, apart from small energy losses due to the friction of the vibrating electrons in the surface. This is why metals such as silver and aluminum are so shiny. They reflect almost all the frequencies of visible light. Smooth surfaces of these metals are therefore used as mirrors.



◀ **Figure 29.2**
When the wave reaches the heavy spring, it is partially reflected. Part of the wave energy bounces back along the first spring, while the other part travels along the heavy spring.

Other materials such as glass and water are not as rigid to light waves. Like the different springs of Figure 29.2, wave energy is both reflected and transmitted at the boundary. When light shines perpendicularly on the surface of still water, about 2% of its energy is reflected and the rest is transmitted. When light strikes glass perpendicularly, about 4% of its energy is reflected. Except for slight losses, the rest is transmitted.

29.2 The Law of Reflection

In one dimension, reflected waves simply travel back in the direction from which they came. Let a ball drop to the floor, and it bounces straight up along its initial path. In two dimensions, the situation is a little different. Toss a ball at an angle to the floor, and it normally bounces at the same angle in a new direction. Likewise with light.

The direction of incident and reflected waves is best described by straight-line *rays.* Incident rays and reflected rays make equal

Important Terms

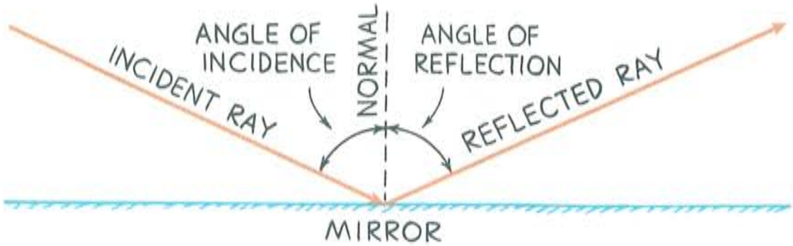
angle of incidence
angle of reflection
law of reflection
normal

All rays from a small source diverge. Far away in a small region, they don't diverge as much (sun's rays near earth are nearly parallel).

Analogy for reflection: a billiard ball (with no spin) bouncing off the cushion of a billiard table at an angle.

angles with a line perpendicular to the surface, called the **normal,** as shown in Figure 29.3. The angle made by the incident ray and the normal, called the **angle of incidence,** is equal to the angle made by the reflected ray and the normal, called the **angle of reflection.** That is,

$$\text{angle of incidence} = \text{angle of reflection}$$



igure 29.3 ▶
n reflection, the angle between he incident ray and the normal s equal to the angle between he reflected ray and the normal.

This relationship is called the **law of reflection.** The incident ray, the normal, and the reflected ray all lie in the same plane. The law of reflection applies to both partially reflected and totally reflected waves.

29.3 Mirrors

Consider a candle flame placed in front of a plane (flat) mirror. Rays of light are reflected from the mirror surface in all directions. The number of rays is infinite, and every one obeys the law of reflection.

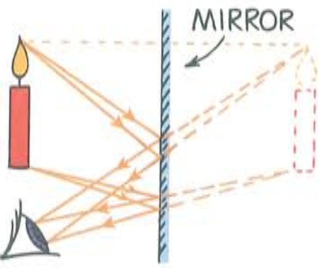
nportant Term

irtual image

you follow the rays of your ght arm to your eye, they will roject back into the mirror as our twin's left arm.

version in mirror is not left to ght, but front to back.

emonstration: You can show eflections from curved mirrors icely using a shiny tablespoon a tin plate.



gure 29.4 ▲
virtual image is formed behind e plane mirror and is located at e position where the extended flected rays (broken lines) nverge.

DOING PHYSICS

Mirror Image

Look at your face in a mirror. Then look at something on the surface of the mirror, such as a dust speck. Notice that you have to adjust your eyes as you refocus from looking at your image to looking at the mirror surface. Is it apparent that your image is farther away than the mirror surface? How much farther? Use a manual focus camera to help you determine these distances. To do this, focus on the dust speck on the mirror surface and then read the distance off the scale on the camera's lens. Repeat this process using your image in the mirror.

When the mirror is curved, the sizes and distances of object and image are no longer equal. This text will not treat curved mirrors, except to say that the law of reflection still holds for curved mirrors. At every part of the surface, the angle of incidence is equal to the angle of reflection, as shown in Figure 29.6. Note that for a curved mirror, unlike a plane mirror, the normals (shown as dashed black lines) at different points on the surface are not parallel to each other.

Activity

Figure 29.4 shows only two rays that originate at the tip of the candle flame and reflect from the mirror to your eye. Note that the rays diverge (spread apart) from the tip of the flame, and continue diverging from the mirror upon reflection. These divergent rays *appear* to originate from a point located behind the mirror. So you see an *image* of the candle in the mirror (actually *behind* the mirror). The image is called a **virtual image,** because light does not actually start there.

Your eye cannot ordinarily tell the difference between an object and its virtual image. This is because the light that enters your eye is entering in exactly the same manner, physically, as it would without the mirror if there really were an object there. Notice that the image is as far behind the mirror as the object is in front of the mirror. Notice also that the image and object are the same size. When you view yourself in a mirror, your image is the same size your identical twin would appear if located as far behind the mirror as you are in front—as long as the mirror is flat.

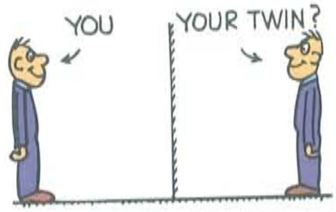
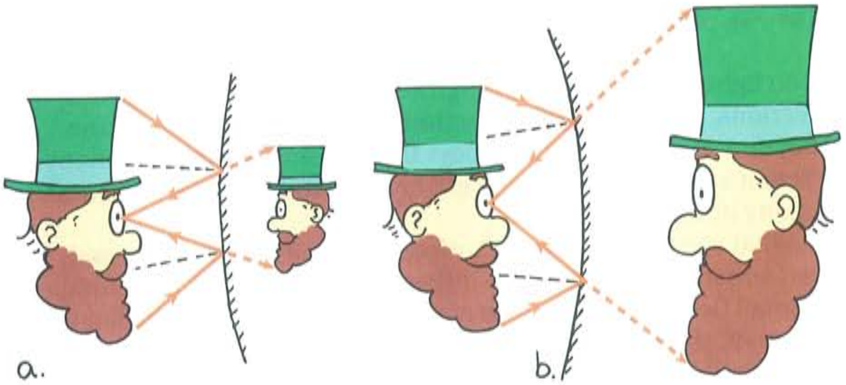


Figure 29.5 ▲
For reflection in a plane mirror, object size equals image size and object distance equals image distance.



◄ **Figure 29.6**
(a) The virtual image formed by a *convex* mirror (a mirror that curves outward) is smaller and closer to the mirror than the object is. (b) When the object is close to a *concave* mirror (a mirror that curves inward like a "cave"), the virtual image is larger and farther away than the object is. In any case, the law of reflection holds for each ray.

Questions

1. If you look at your blue shirt in a mirror, what is the color of its image? What does this tell you about the frequency of light incident upon a mirror compared with the frequency of the light after it is reflected?
2. If you wish to take a picture of your image while standing 2 m in front of a plane mirror, for what distance should you set your camera to provide sharpest focus?

The Best From Conceptual Physics Alive!

Image Formation in a Mirror

Side 3
Chapter 22

Answers

1. The color of the image will be the same as the color of the object. This is evidence that the frequency of light is not changed by reflection.
2. You should set your camera for a distance of 4 m. The situation is equivalent to your standing 2 m in front of an open window and viewing your twin standing 2 m in back of the window.

DOING PHYSICS

Multiplying Money

Stand a pair of mirrors on edge with their faces at 90°. Place a coin close to where the mirrors meet. How many coins do you see? Now make the angle between the mirrors smaller and smaller. What happens to the number of coin images? Finally, adjust the mirrors so that they are parallel and facing each other, only a few centimeters apart with the coin in between. How many images are there? Lots! How much money is there? Unfortunately there is still only one coin.

Activity

29.4 Diffuse Reflection

Important Term

diffuse reflection

When light is incident on a rough surface, it is reflected in many directions. This is **diffuse reflection** (Figure 29.7). Although the reflection of each single ray obeys the law of reflection, the many different angles that incident light rays encounter cause reflection in many directions.

What constitutes a rough surface for some rays may be a polished surface for others. If the differences in elevations in a surface are small (less than about one-eighth the wavelength of the light that falls on it), the surface is considered polished. A surface therefore may be polished for long wavelengths, but not polished for short wavelengths. The wire-mesh "dish" shown in Figure 29.8 is very rough for light waves, not mirrorlike at all. Yet for long-wavelength radio waves, it is polished. It acts as a mirror to radio waves and is an

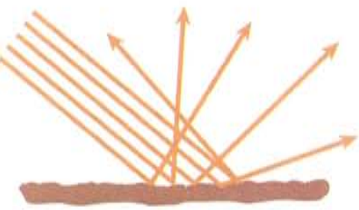


Figure 29.7 ▲
Diffuse reflection from a rough surface.

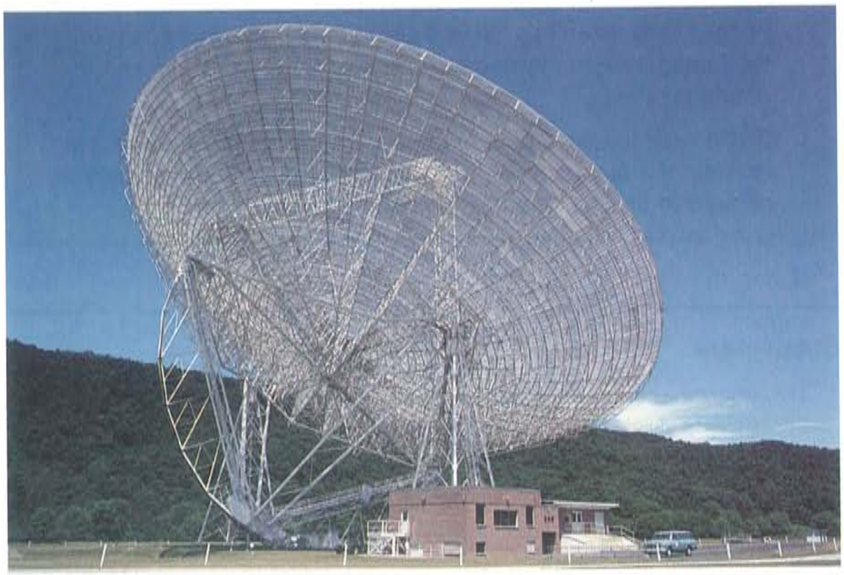


Figure 29.8 ▶
The open-mesh parabolic dish acts like a diffuse reflector for light waves but like a polished reflector for long-wavelength radio waves.

excellent reflector. Whether a surface is a diffuse reflector or a polished reflector depends on the length of the waves it reflects.

Light that reflects from this page is diffuse. The page may be smooth to a long radio wave, but to the short wavelengths of visible light it is rough. This roughness is evident in the microscopic view of an ordinary paper surface (Figure 29.9). Rays of light incident on this page encounter millions of tiny flat surfaces facing in all directions, so they are reflected in all directions. This is very nice, for it allows us to read the page from any direction or position. We see most of the things around us by diffuse reflection.

Figure 29.9 ▲
A microscopic view of the surface of ordinary paper.

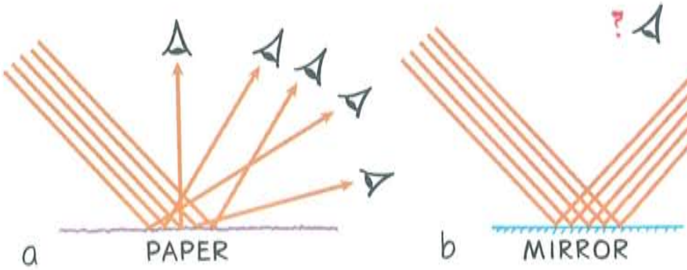


Figure 29.10 ▲
(a) If you shine a beam of light on paper, you can see diffusely reflected light at any position. (b) However, your eye must be at the right place to see a reflected beam from a small mirror.

Important Term

reverberation

29.5 Reflection of Sound

An echo is reflected sound. The fraction of sound energy reflected from a surface is more when the surface is rigid and smooth, and less when the surface is soft and irregular. Sound energy not reflected is absorbed or transmitted.

Sound reflects from all surfaces—the walls, ceiling, floor, furniture, and people—of a room. Designers of interiors of buildings, whether office buildings, factories, or auditoriums, need to understand the reflective properties of surfaces. The study of these properties is *acoustics.*

When the walls of a room, auditorium, or concert hall are too reflective, the sound becomes garbled. This is due to multiple reflections called **reverberations.** But when the reflective surfaces are more absorbent, the sound level is lower, and the hall sounds dull and lifeless. Reflection of sound in a room makes it sound lively and full, as you have probably found out while singing in the shower. In the design of an auditorium or concert hall, a balance between reverberation and absorption is desired.

The walls of concert halls are often designed with grooves so that the sound waves are diffused. This is illustrated in Figure 29.11 (top). In this way a person in the audience receives a small amount of reflected sound from many parts of the wall, rather than a larger amount of sound from one part of the wall.

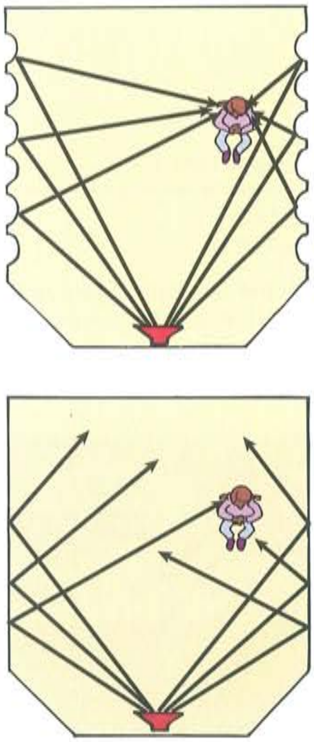
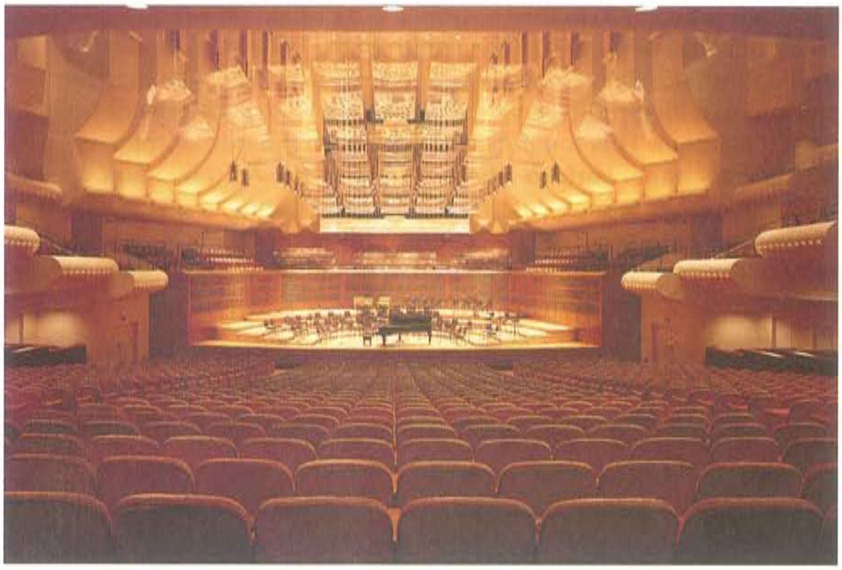


Figure 29.11 ▲
(Top) With grooved walls, sound reflects from many small sections of the wall to a listener. (Bottom) With flat walls, an intense reflected sound comes from only one part of the wall.



gure 29.12 ▶
e disks above the orchestra in
avies Symphony Hall in San
ancisco reflect both light and
und. Adjusting them is quite
mple: What you see is what
u hear.

Highly reflective surfaces are often placed behind and above the stage to direct sound out to an audience. The large shiny plastic disks in Figure 29.12 also reflect light. A listener can look up at these reflectors and see the reflected images of the members of the orchestra. (The plastic reflectors are somewhat curved, which increases the field of view.) Both sound and light obey the same law of reflection, so if a reflector is oriented so that you can *see* a particular musical instrument, rest assured that you will *hear* it also. Sound from the instrument will follow the line of sight to the reflector and then to you.

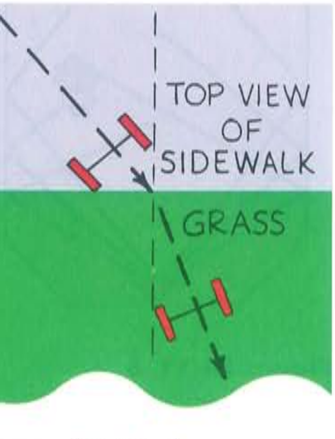
portant Terms

fraction
ave front

aw the perpendiculars to the
ave front and the normal to
e boundary, and show the
ange in direction.

29.6 Refraction

Suppose you take a rear axle with its wheels attached off an old toy cart and let it roll along a pavement that slopes gently downward and onto a downward-sloping mowed lawn. It rolls more slowly on the lawn because of the interaction of the wheels with the blades of grass. If you roll it at an angle as shown in Figure 29.13, it will be deflected from its straight-line course. The direction of the axle and rolling wheels is shown in the illustration. Note that the wheel that first meets the lawn slows down first—because it interacts with the grass while the opposite wheel is still rolling on the pavement. The axle pivots, and the path is bent toward the normal (the thin dashed line perpendicular to the grass-pavement boundary). The axle then continues across the lawn in a straight line at reduced speed.



gure 29.13 ▲
e direction of the rolling
heels changes when one wheel
ows down before the other one.

Water waves similarly bend when one part of each wave is made to travel slower (or faster) than another part. This is **refraction.** Waves travel faster in deep water than in shallow water. Figure 29.14 (left) shows a view from above of straight wave crests (the bright lines) moving toward the right edge of the photo. They are moving from deep water across a diagonal boundary into shallow water. At the boundary,

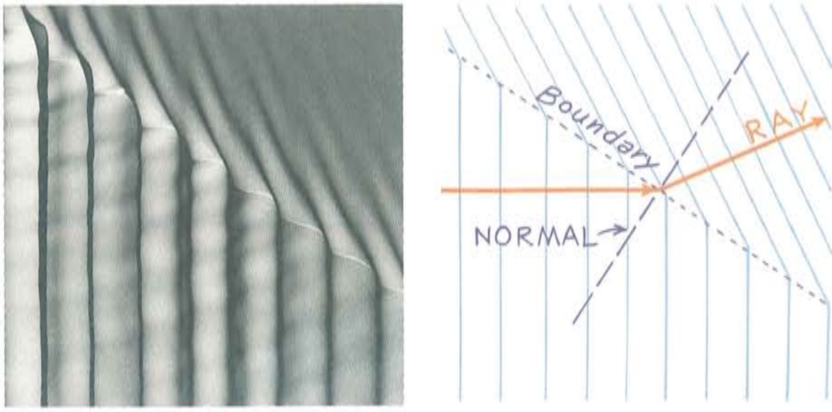


Figure 29.14 ▲
(Left) Photograph of the refraction of a water wave at a boundary where the wave speed changes because the water depth changes. (Right) Diagram of wave fronts and a sample ray. The ray is perpendicular to the wave front it intersects.

The Best From Conceptual Physics Alive!
Demo: Model of Refraction
Side 3
Chapter 23

the wave speed and direction of travel are abruptly altered. Since the wave moves more slowly in shallow water, the crests are closer together. If you look carefully, you'll see some reflection from the boundary.

In drawing a diagram of a wave, as in Figure 29.14 (right), it is convenient to draw lines that represent the positions of different crests. Such lines are called **wave fronts.*** At each point along a wave front, the wave is moving perpendicular to the wave front. The direction of motion of the wave can thus be represented by rays that are perpendicular to the wave fronts. The ray in Figure 29.14 (right) shows how the water wave changes direction after it crosses the boundary between deep and shallow water. Sometimes we analyze waves in terms of wave fronts, and at other times in terms of rays. Both are useful models for understanding wave behavior.

29.7 Refraction of Sound

Sound waves are refracted when parts of a wave front travel at different speeds. This happens in uneven winds or when sound is traveling through air of uneven temperature. On a warm day, for example, the air near the ground may be appreciably warmer than the air above. Since sound travels faster in warmer air, the speed of sound near the ground is increased. The refraction is not abrupt but gradual (Figure 29.15). Sound waves therefore tend to bend away from warm ground, making it appear that the sound does not carry well.

Demonstration: If you place a speaker in front of a balloon filled with CO_2 and put your ear on the opposite side, the bending of sound focuses the waves. You have made an acoustical lens.

* Wave fronts can also represent the positions of different troughs—or any continuous portions of the wave that are all vibrating the same way at the same time.

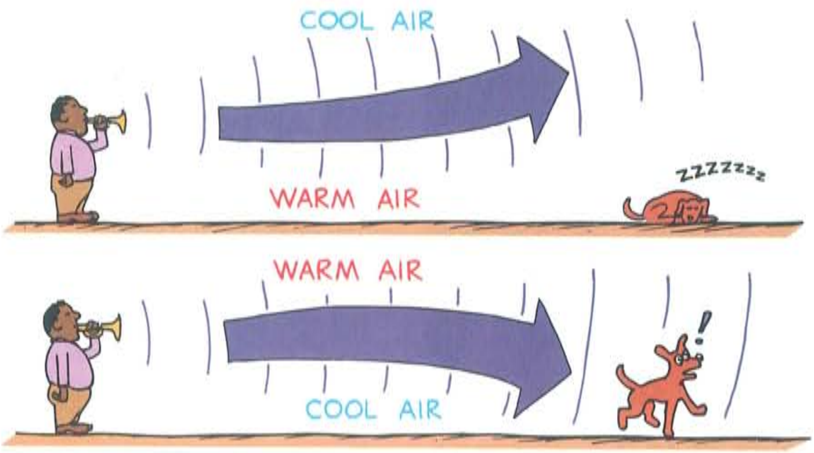


Figure 29.15 ▲
The wave fronts of sound are bent in air of uneven temperature.

On a cold day or at night, when the layer of air near the ground is colder than the air above, the speed of sound near the ground is reduced. The higher speed of the wave fronts above cause a bending of the sound toward the earth. When this happens, sound can be heard over considerably longer distances.

The Best From Conceptual Physics Alive!
Refraction of Sound
Side 3
Chapter 24

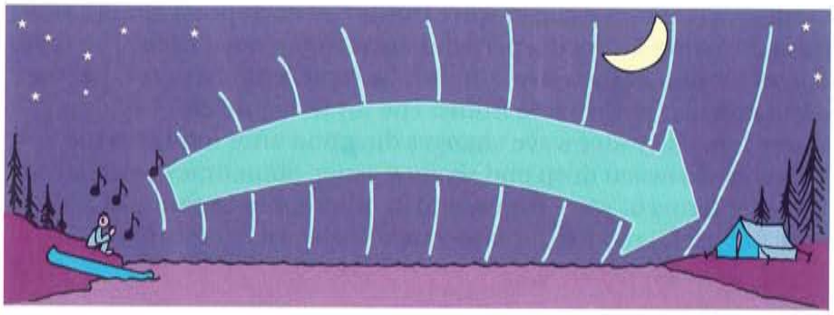


Figure 29.16 ▲
At night, when the air is cooler over the surface of the lake, sound is refracted toward the ground and carries unusually well.

■ Question

Suppose you are downwind from a factory whistle. In which case will the whistle sound louder—if the wind speed near the ground is more than the wind speed several meters above the ground, or if it is less?

■ Answer

You'll hear the whistle better if the wind speed near the ground is less than the wind speed higher up. For this condition, the sound will be refracted toward the ground. If the wind speed were greater near the ground, the refraction would be upward.

29.8 Refraction of Light

A pond or swimming pool both appear shallower than they actually are. A pencil in a glass of water appears bent, the air above a hot stove seems to shimmer, and stars twinkle. These effects are caused by changes in the speed of light as it passes from one medium to another, or through varying temperatures and densities of the same medium—which changes the directions of light rays. In short, these effects are due to the refraction of light.*

Figure 29.17 shows rays and wave fronts of light refracted as it passes from air into water. (The wave fronts would be curved if the source of light were close, just as the wave fronts of water waves near a stone thrown into the water are curved. If we assume that the source of light is the sun, then it is so far away that the wave fronts are practically straight lines.) Note that the left portions of the wave fronts are the first to slow down when they enter the water (or right portion if you look along the direction of travel). The refracted ray of light, which is at right angles to the refracted wave fronts, is closer to the normal than is the incident ray.

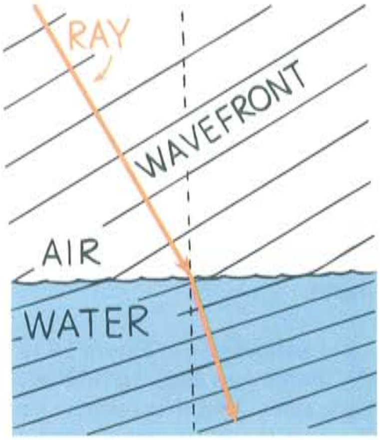


Figure 29.17 ▲
As a light wave passes from air into water, its speed decreases. Note that the refracted ray is closer to the normal than is the incident ray.

Compare the refraction in this case to the bending of the axle's path in Figure 29.13. When light rays enter a medium in which their speed decreases, as when passing from air into water, the rays bend toward the normal. But when light rays enter a medium in which their speed increases, as when passing from water into air, the rays bend away from the normal.

Figure 29.18 shows a laser beam entering a container of water at the left and exiting at the right. The path would be the same if the light entered from the right and exited at the left. The light paths are reversible for both reflection and refraction. If you can see somebody by way of a reflective or refractive device, such as a mirror or a prism, then that person can see you (or your eyes) by looking through the device also.

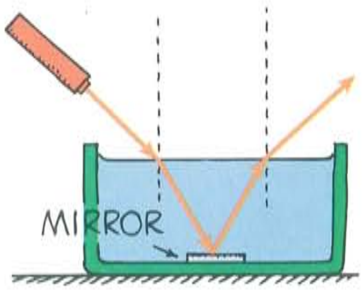


Figure 29.18 ▲
The laser beam bends toward the normal when it enters the water, and away from the normal when it leaves.

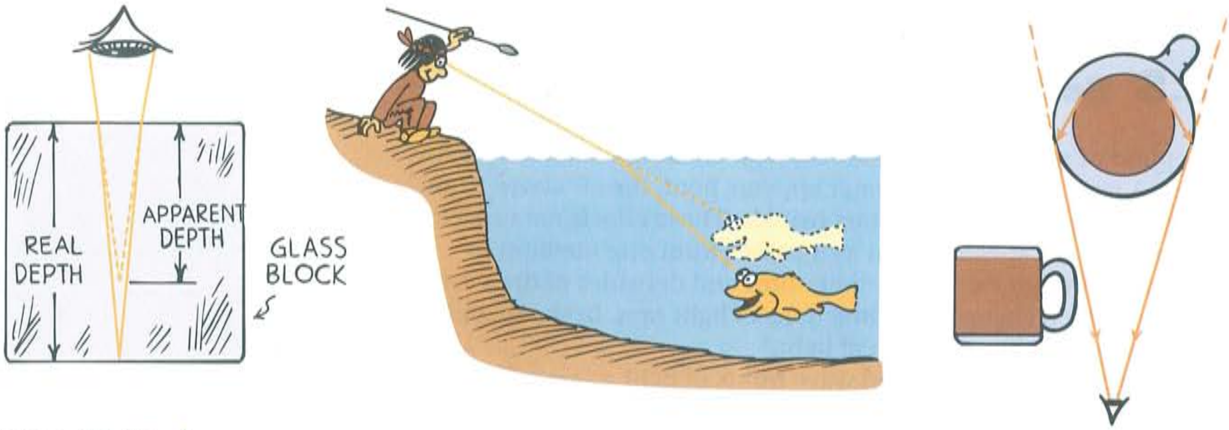
* The ratio n of the speed of light in a vacuum to the speed in a given material is called the *index of refraction* of that material.

$$\text{index of refraction } n = \frac{\text{speed of light in vacuum}}{\text{speed of light in material}}$$

The quantitative law of refraction, called *Snell's law*, was first worked out in 1621 by W. Snell, a Dutch astronomer and mathematician. According to Snell's law,

$$n \sin \theta = n' \sin \theta'$$

where n and n' are the indices of refraction of the media on either side of the boundary, and θ and θ' are the respective angles of incidence and refraction. If three of these values are known, the fourth can be calculated from this relationship.



igure 29.19 ▲
ecause of refraction, the appar-
nt depth of the glass block is
ss than the real depth (left), the
sh appears to be nearer than it
tually is (center), and the full
ass mug appears to hold more
ot beer than it actually does
ght).

ght behaves as in Figure 29.19
ft, in mirrors silvered on the
ack side. Light first refracts as
enters the glass, then reflects
f the back surface, then re-
acts when it leaves the glass.

you extend the ray from
e fish's eye backwards, you
e that the fish sees the per-
on to be higher than he or
e really is.

nportant Term

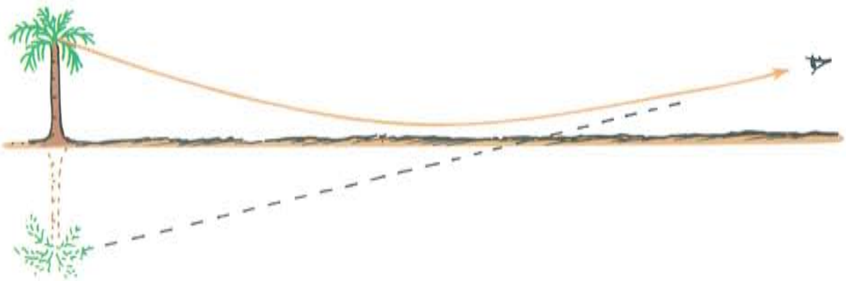
irage

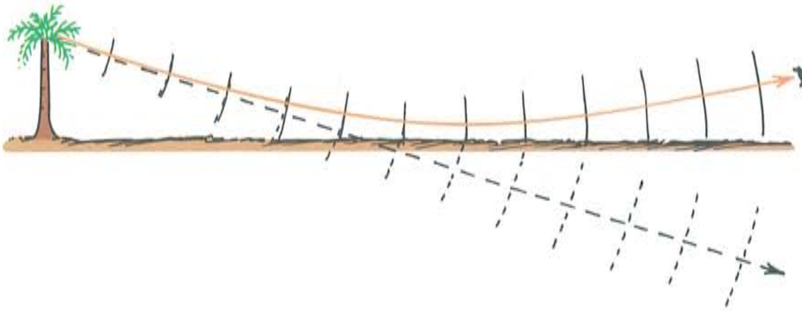
As Figure 29.19 (left) shows, a thick pane of glass appears to be only two-thirds its real thickness when viewed straight on. (For clarity, the diameter of the eye pupil is made larger than true scale.) Similarly, water in a pond or pool appears to be only three-quarters its true depth. Look at a fish in water from a bank, and the fish appears to be nearer the surface than it really is (Figure 29.19, center). It also seems closer. Another illusion is shown in the right of the figure. Light from the root beer is refracted through the sides of the thick glass, making the glass appear thinner than it is. The eye, accustomed to perceiving light traveling along straight lines, perceives the root beer to be at the outer edge of the glass, along the broken lines. These effects are due to the refraction of light whenever it crosses a boundary between air and another transparent medium.

29.9 Atmospheric Refraction

Although the speed of light in air is only 0.03% less than its speed in a vacuum, in some situations atmospheric refraction is quite noticeable. One interesting example is the **mirage.** On hot days there may be a layer of very hot air in contact with the ground. Since molecules in hot air are farther apart, light travels faster through it than through cooler air above. The speeding up of the part of the wave nearest the ground produces a gradual bending of the light rays. This can produce an image, say, of the tree in Figure 29.20. The image appears upside down to an observer at the right, just as if it were reflected from a surface of water. But the light is not reflected; it is refracted.

gure 29.20 ▶
e refraction of light in air
oduces a mirage.





◀ **Figure 29.21**
Wave fronts of light travel faster in the hot air near the ground, thereby bending the rays of light upward.

Wave fronts of light are shown in Figure 29.21. The refraction of light in air in this case is very much like the refraction of sound in Figure 29.15. Undeflected wave fronts would travel at one speed and in the direction shown by the broken lines. Their greater speed near the ground, however, causes the light ray to bend upward as shown.

A motorist experiences a similar situation when driving along a hot road that appears to be wet ahead. The sky appears to be reflected from a wet surface but, in fact, light from the sky is being refracted through a layer of hot air. A mirage is not, as some people mistakenly believe, a "trick of the mind." A mirage is formed by real light and can be photographed (see Figure 29.22).

◀ **Figure 29.22**
A mirage.

Students often say they can see the "heat waves" near the ground. In fact, these are air convection currents much like their counterparts in heated water.

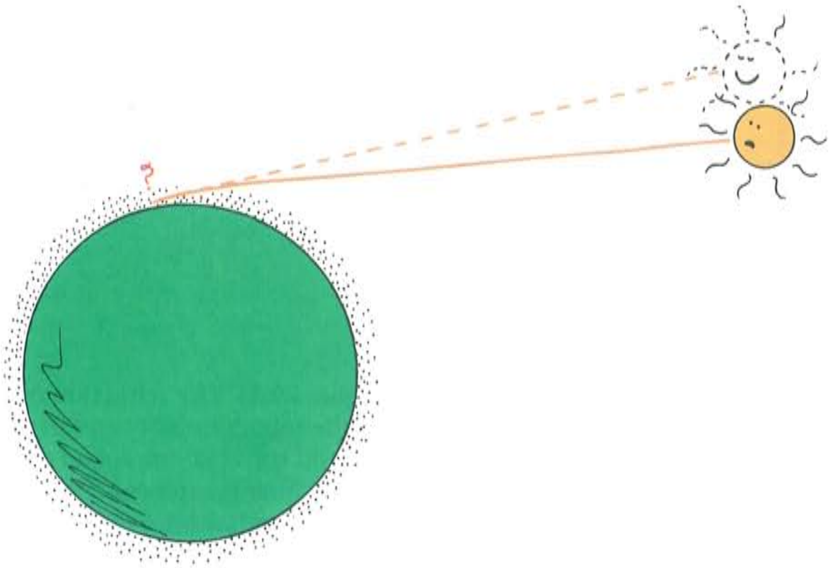
DOING PHYSICS

Refraction in Air

Look across a hot stove or hot pavement. Those shimmering images, or "heat waves," you see are the effects of atmospheric refraction. The speed of light changes as it travels through varying temperatures and densities of air. Similarly, the twinkling of stars in the nighttime sky is produced by refractions of light as it passes through unstable layers in the atmosphere. Do you see one reason why many observatories are located atop mountains?

Activity

igure 29.23 ▶
Vhen the sun is already below
ne horizon, you can still see it.



igure 29.24 ▲
tmospheric refraction produces
"pumpkin" sun.

When you watch the sun set, you see the sun for several minutes after it has really sunk below the horizon. This is because light is refracted by the earth's atmosphere (Figure 29.23). Since the density of the atmosphere changes gradually, the refracted rays bend gradually to produce a curved path. The same thing occurs at sunrise, so our daytimes are about 5 minutes longer because of atmospheric refraction.

When the sun (or moon) is near the horizon, the rays from the lower edge are bent more than the rays from the upper edge. This produces a shortening of the vertical diameter and makes the sun (or moon) look elliptical instead of round (Figure 29.24).

Question

If the speed of light were the same for the various temperatures and densities of air, would there still be mirages, slightly longer daytimes, and a "pumpkin" sun at sunset?

29.10 Dispersion in a Prism

nportant Term

ispersion

Chapter 27 discussed how the average speed of light is less than *c* in a transparent medium. How much less depends on the medium and the frequency of the light. Light of frequencies closer to the natural frequency of the electron oscillators in a medium travels more slowly in the medium. This is because there are more interactions with the

Answer

No! There would be no refraction if light traveled at the same speed in air of different temperatures and densities.

medium in the process of absorption and reemission. Since the natural or resonant frequency of most transparent materials is in the ultraviolet part of the spectrum, visible light of higher frequencies travels more slowly than light of lower frequencies. Violet light travels about 1% slower in ordinary glass than red light. The colors between red and violet travel at their own intermediate speeds.

Since different frequencies of light travel at different speeds in transparent materials, they will refract differently and bend at different angles. When light is bent twice at nonparallel boundaries, as in a prism, the separation of the different colors of light is quite apparent. This separation of light into colors arranged according to their frequency is called **dispersion** (Figure 29.25). Dispersion is what enabled Isaac Newton to produce a spectrum.

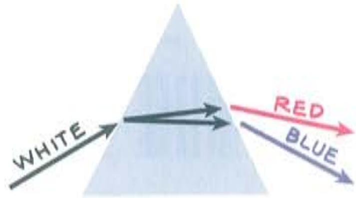


Figure 29.25 ▲
Dispersion through a prism.

The separation occurs because the sides of the triangular prism (and raindrop) are not parallel. Light does not disperse in an angle as it passes through a window because its sides are parallel.

29.11 The Rainbow

A spectacular illustration of dispersion is the rainbow. The conditions for seeing a rainbow are that the sun be shining in one part of the sky and that water droplets in a cloud or in falling rain be in the opposite part of the sky. When you turn your back to the sun, you see the spectrum of colors in a bow. Seen high enough from an airplane, the bow forms a complete circle. All rainbows would be completely round if the ground were not in the way.

See the "Rainbow-sticks-and-ball" device described in the Teaching Guide.

Figure 29.26 shows a single arc. The thicker the raindrop region, the more arcs and the brighter the bow. The arcs can be thought of as concentric rings around a cone with apex at the viewer's eye.

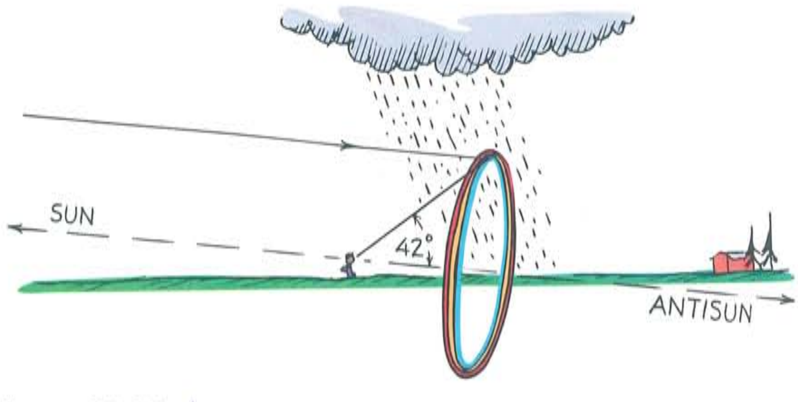


Figure 29.26 ▲
The rainbow is seen in a part of the sky opposite the sun and is centered on the imaginary line extending from the sun to the observer.

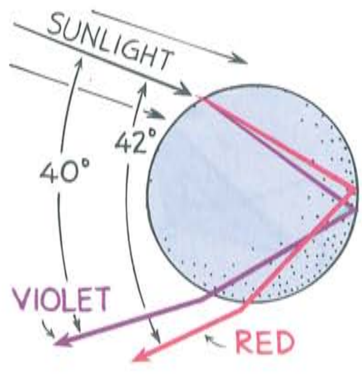


Figure 29.27 ▲
Dispersion of sunlight by a single drop, which produces a rainbow. Light is concentrated at the angles shown.

To understand how light is dispersed by raindrops, consider an individual spherical raindrop, as shown in Figure 29.27. Follow the ray of sunlight as it enters the drop near its top surface. Some of the light here is reflected (not shown), and the rest is refracted into the water. At this first refraction, the light is dispersed into its spectral colors. Violet is bent the most and red the least.

The Best From Conceptual Physics Alive!

he Rainbow

.Side 3
Chapter 26

The rays reach the opposite part of the drop to be partly refracted out into the air (not shown) and partly reflected back into the water. Part of the rays that arrive at the lower surface of the drop are refracted into the air. This second refraction is similar to that of a prism, where refraction at the second surface increases the dispersion already produced at the first surface. This twice-refracted, once-reflected light is concentrated in a narrow range of angles.

Each drop disperses a full spectrum of colors. An observer, however, is in a position to see only a single color from any one drop (see Figure 29.28). If violet light from a single drop enters your eye, red light from the same drop falls below your eye. To see red light you have to look at a drop higher in the sky. You'll see the color red when the angle between a beam of sunlight and the dispersed light is 42°. The color violet is seen when the angle between the sunbeam and dispersed light is 40°.

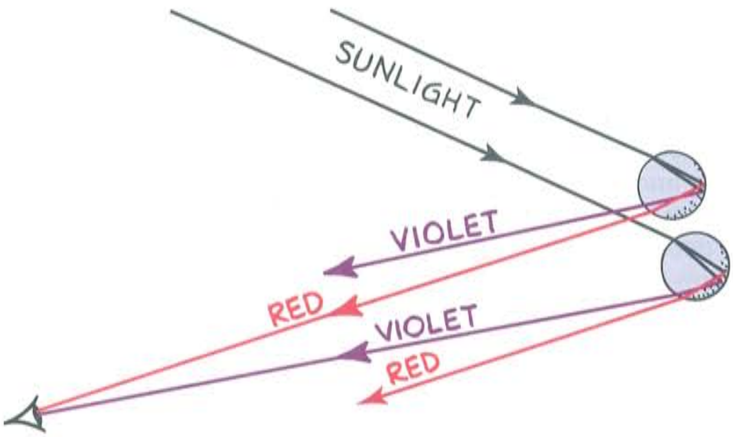
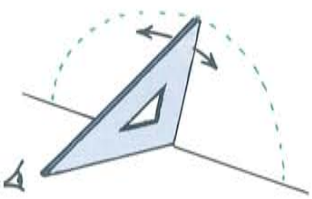


Figure 29.28 ▲
Sunlight strikes two sample drops and emerges as dispersed light. The observer sees red from the upper drop and violet from the lower drop. Millions of drops produce the whole spectrum.



igure 29.29 ▲
nly raindrops along the dashed rc disperse red light to the bserver at a 42° angle.

You don't need to look only upward at 42° to see dispersed red light. You can see red by looking sideways at the same angle or anywhere along a circular arc swept out at a 42° angle (see Figure 29.29). The dispersed light of other colors is along similar arcs, each at their own slightly different angle. Altogether, the arcs for each color form the familiar rainbow shape.

If you rotate the triangle in Figure 29.29 you sweep out the portion of a cone, with your eye at the apex. The raindrops that disperse light to you lie at the far edges of such a cone. The thicker the region of water drops, the thicker the conical edge you look through, and the more vivid the rainbow.

Your cone of vision that intersects the raindrops creating your rainbow is different from that of a person next to you. So when a friend says, "Look at the beautiful rainbow," you can reply, "Okay, move aside so I can see it too." Everybody sees his or her own personal rainbow.

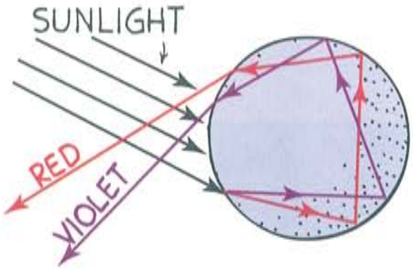


Figure 29.30
Double reflection in a drop produces a secondary bow.

So when you move, your rainbow moves with you. This means you can never approach the side of a rainbow, or see it end-on as in the exaggerated view of Figure 29.26. You *can't* get to its end. Hence the expression "looking for the pot of gold at the end of the rainbow" means pursuing something you can never reach.

Often a larger, secondary bow with colors reversed can be seen arching at a greater angle around the primary bow. The secondary bow is formed by similar circumstances and is a result of double reflection within the raindrops (Figure 29.30). Because some light is refracted out the back during the extra reflection, the secondary bow is much dimmer.

Question

If light traveled at the same speed in raindrops as it does in air, would we still have rainbows?

29.12 Total Internal Reflection

Important Terms

critical angle
optical fiber
total internal reflection

Demonstration: Internal reflection can be nicely demonstrated with a laser or other narrow beam source by shining it through the side of a fish tank up to the surface.

When you're in a physics mood and you're going to take a bath, fill the tub extra deep and bring a waterproof flashlight into the tub with you. Turn the bathroom light off. Shine the submerged light straight up and then slowly tip it and note how the intensity of the emerging beam diminishes and how more light is reflected from the water surface to the bottom of the tub.

At a certain angle, called the **critical angle,** you'll notice that the beam no longer emerges into the air above the surface. The intensity of the emerging beam reduces to zero where it tends to graze the surface. When the flashlight is tipped beyond the critical angle (48° from the normal in water), you'll notice that the beam cannot enter the air; it is only reflected. The beam is experiencing **total internal reflection.** The only light emerging from the water surface is that which is diffusely reflected from the bottom of the bathtub.

Answer

No.

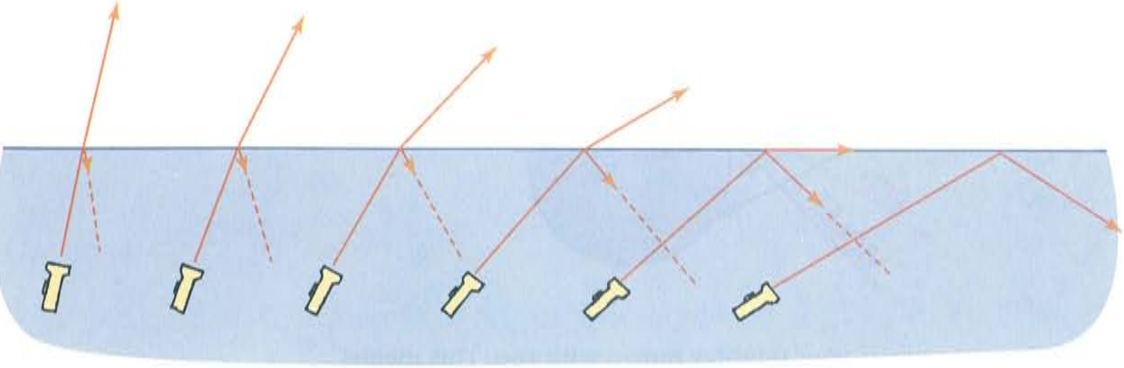


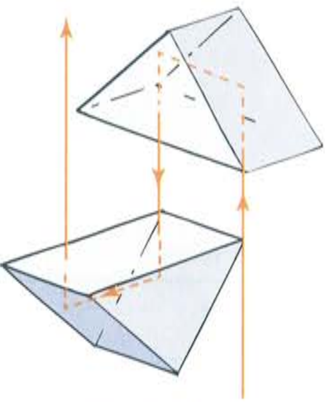
Figure 29.31 ▲
Light emitted in the water at angles below the critical angle is partly refracted and partly reflected at the surface. At the critical angle (second sketch from right), the emerging beam skims the surface. Past the critical angle (far right), there is total internal reflection.

This procedure is shown in Figure 29.31. The proportions of light refracted and reflected are indicated by the relative lengths of the solid arrows. Note that the light reflected beneath the surface obeys the law of reflection: The angle of incidence is equal to the angle of reflection.

The critical angle for glass is about 43°, depending on the type of glass. This means that within the glass, rays of light that are more than 43° from the normal to a surface will be totally internally reflected at that surface. Rays of light in the glass prisms shown in Figure 29.32, for example, meet the back surface at 45° and are totally internally reflected. They will stay inside the glass until they meet a surface at an angle between 0° (straight on) and 43° to the normal.

Total internal reflection is as the name implies: total—100%. Silvered or aluminized mirrors reflect only 90 to 95% of incident light, and are marred by dust and dirt; prisms are more efficient. This is the main reason they are used instead of mirrors in many optical instruments.

The critical angle for a diamond is 24.6°, smaller than any other known substance. This small critical angle means that light inside a



igure 29.32 ▲
otal internal reflection in glass risms.

he mineral hematite (Fe_2O_3) as an even smaller critical ngle, 18.9°.

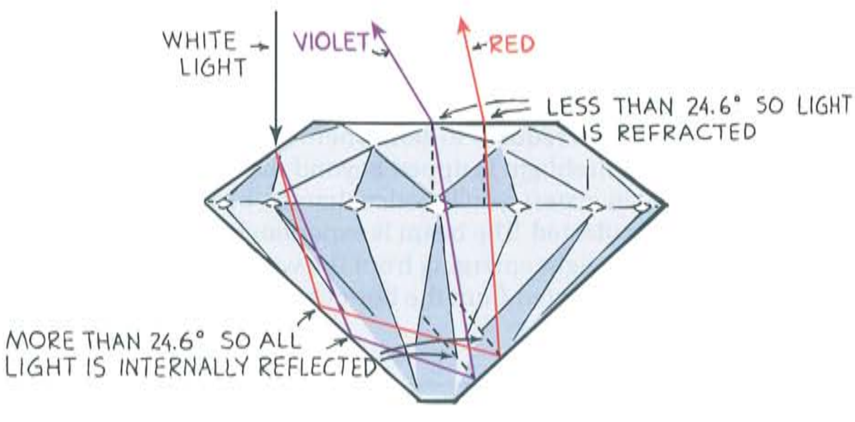
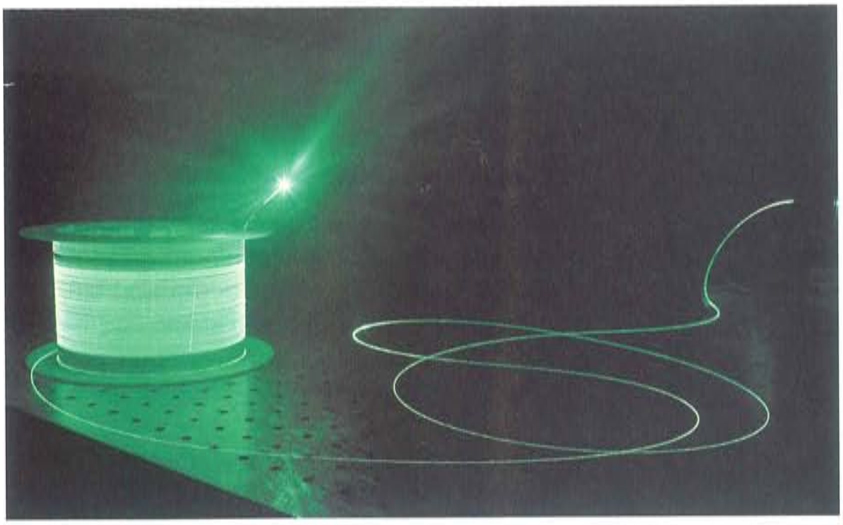


Figure 29.33 ▲
Paths of light in a diamond.



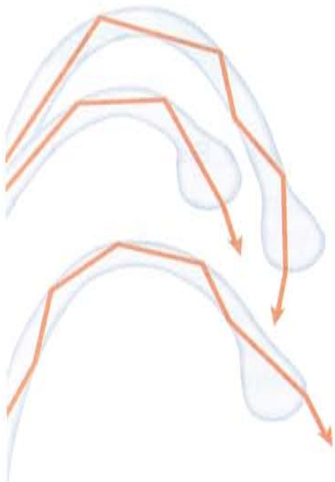


Figure 29.34 ▲
In an optical fiber, light is piped from one end to the other by a succession of total internal reflections.

diamond is more likely to be totally internally reflected than to escape. All light rays more than 24.6° from the normal to a surface in a diamond stay inside by total internal reflection. When a diamond is cut as a gemstone, light that enters at one facet is usually totally internally reflected several times, without any loss in intensity, before exiting from another facet in another direction. That's why you see unexpected flashes from a diamond. A small critical angle, plus the pronounced refraction because of the unusually low speed of light in diamond, produces wide dispersion and a wide array of colors. The colors seen in a diamond are quite brilliant.

Total internal reflection underlies the usefulness of **optical fibers,** sometimes called *light pipes.* As the name implies, these transparent fibers pipe light from one place to another. They do this by a series of total internal reflections, much like the ricocheting of a bullet inside a steel pipe. Optical fibers are useful for getting light to inaccessible places. Mechanics and machinists use them to look at the interior of engines, and physicians use them to look inside a patient's body. Light shines down some of the fibers to illuminate the scene and is reflected back along others.

Optical fibers are important in communications. In many cities, thin glass fibers have replaced thick, bulky, and expensive copper cables to carry thousands of simultaneous telephone messages between major switching centers. Undersea copper cables are also being replaced by optical fibers. More information can be carried in the high frequencies of visible light than in the lower frequencies of electric current. Optical fibers are more and more replacing electric circuits and microwave links in communications technology.

LINK TO BIOLOGY

Fiber-Optic Bears

Ever wonder how a polar bear survives the extreme cold of an arctic winter? Fiber optics of course! The polar bear's fur provides more than insulation against the cold; the hairs of its fur are actually transparent optical fibers that trap ultraviolet light. A polar bear's fur appears white because visible light is reflected by the rough inner surface of each hollow hair. Higher-frequency radiant energy shines down the fibers to the bear's skin. The skin is very efficient at absorbing all the solar energy it can get—guess what color the skin is? Black!

29 Chapter Review

For fuller explanations, see the TE notes in the front of this book.

Concept Summary

n reflection, a wave reaches the boundary etween two media and bounces back into the rst medium.

At a boundary, usually part of a wave is reflected and part passes into the second medium.

According to the law of reflection, the angle of incidence is equal to the angle of reflection.

A plane mirror forms a virtual image of an object; the image appears to be as far in back of the mirror as the object is in front of it, and is the same size as the object.

Light that falls on a rough surface is reflected diffusely.

refraction, a wave reaches the boundary etween two media and changes direction as it asses into the second medium.

Refraction is caused by a difference in the speed of the wave in the two media.

The speed of light in materials depends on frequency, causing the different colors that make up white light to refract differently and spread out to form a visible spectrum.

total internal reflection, an incident wave on a oundary is at an angle such that none of the ave can be refracted, so only reflection occurs.

nportant Terms

gle of incidence (29.2
gle of reflection (29.2)
itical angle (29.12)
ffuse reflection (29.4)
spersion (29.10)
v of reflection (29.2)
irage (29.9)
ormal (29.2)
optical fiber (29.12)
reflection (29.1)
refraction (29.6)
reverberation (29.5)
total internal reflection (29.12)
virtual image (29.3)
wave front (29.6)

Review Questions

Recall of key chapter ideas

1. What becomes of a wave's energy when the wave is totally reflected at a boundary? When it is partially reflected at a boundary? (29.1)
Goes back in orig medium; part into second medium
2. Why do smooth metal surfaces make good mirrors? (29.1) Reflect almost all the colors of visible light
3. When light strikes perpendicular to the surface of a pane of glass, how much light is reflected and how much is transmitted? (29.1)
4% reflected; 96% transmitted (at first surface)
4. What is meant by the normal to a surface? (29.2) Any line that is perpendicular to the surface
5. What is the law of reflection? (29.2) Angle of incidence = angle of reflection
6. When you view your image in a plane mirror, how far behind the mirror is your image compared with your distance in front of the mirror? (29.3)
Same distance
7. Does the law of reflection hold for *curved* mirrors? (29.3) Yes, though normals not parallel to each other
8. Does the law of reflection hold for diffuse reflection? Explain. (29.4) For each single ray, yes; many rays diffused
9. What is meant by the idea that a surface may be polished for some waves and rough for others? (29.4) Polished if irregularities < (1/8)λ of incident wave
10. Distinguish between an echo and a reverberation. (29.5) Echo, single reflection; reverb, multiple reflections
11. Does the law of reflection hold for both sound waves and light waves? (29.5)
Yes, for all types of waves
12. Distinguish between reflection and refraction. (29.1, 29.6) Refl, waves same medium; refr, goes into 2nd med
13. When a wave crosses a surface at an angle from one medium into another, why does it

"pivot" as it moves across the boundary into the new medium? (29.6) Wave speed changes when entering new medium.

14. What is the orientation of a ray in relation to the wave front of a wave? (29.6) Always perpendicular

15. Give an example where refraction is abrupt, and another where refraction is gradual. (29.6–29.7) From air to water (sharp boundary); in atmosphere

16. Does refraction occur for both sound waves and light waves? (29.7–29.8) Yes, for all types of waves

17. If light had the same speed in air and in water, would light be refracted in passing from air into water? (29.8) No, refraction depends on change in wave speed

18. If you can see the face of a friend who is underwater, can she also see you? (29.8) Yes (eyes at least), direction of rays is reversible

19. Does refraction tend to make objects submerged in water seem shallower or deeper than they really are? (29.8) Shallower

20. Is a mirage a result of refraction or reflection? Explain. (29.9) Refraction (only appears to be reflected)

21. Is daytime a bit longer or a bit shorter because of atmospheric refraction? (29.9) Longer

22. As light passes through glass or water, do the high or low frequencies of light interact more in the process of absorption and reemission, and therefore lag behind? (29.10) High frequencies interact more.

23. Why does blue light refract at greater angles than red light in transparent materials? (29.10) Blue interacts more and slows more than red.

24. What conditions are necessary for viewing a rainbow in the sky? (29.11) Observer between low sun and water drops

25. How is a raindrop similar to a prism? (29.11) Both refract and disperse light

26. What is the *critical angle* in terms of refraction and total internal reflection? (29.12) Angle at which light doesn't refract, but reflects

27. Why are optical fibers often called *light pipes?* (29.12) They literally pipe light along the fiber

Activities

1. What must be the minimum length of a plane mirror in order for you to see a full view of yourself? To find out, stand in front of a mirror and put pieces of tape on the glass: one piece where you see the top of your head, and the other where you see the bottom of your feet. Compare the distance between the pieces of tape with your height. If a full-length mirror is not handy, use a smaller mirror and find the minimum length of mirror to see your face. Mark where you see the top of your head and the bottom of your chin. Then compare the distance between the marks with the length of your face. Mirror need be only half your height

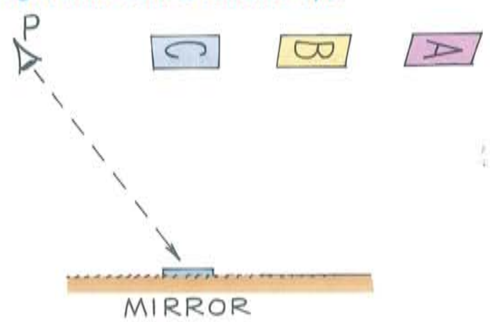
2. What effect does your distance from the mirror have on the answer to Activity 1? (*Hint:* Move closer and farther from your initial position. Be sure the top of your head lines up with the top piece of tape. At greater distances, is your image smaller than, larger than, or the same size as the space between the pieces of tape?) Surprised? No difference; same change for both image and mirror

3. If available, look at a diamond or similar transparent gemstone under bright light. Turn the stone and note the flashes of color that refract, reflect, and refract toward you. When the flash encounters only one eye instead of two, your brain registers it differently than for both eyes. The one-eyed flash is a sparkle!

Think and Explain

Conceptual development through applied critical thinking

1. Suppose that a mirror and three lettered cards are set up as in the figure. If a person's eye is at point P, which of the lettered cards will be seen reflected in the mirror? Only light from card B reaches eye.



. Why is the lettering on the front of some vehicles "backward," as seen here? Reflected view in car mirror reads correctly.

. Trucks often have signs on their backs that say, "If you can't see my mirrors, I can't see you." Explain the physics here. Light path is reversible.

. Contrast the types of reflection from a rough road and from the smooth surface of a wet road to explain why it is difficult for a motorist to see the roadway ahead when driving on a rainy night. Dry road diffuse reflection; wet road mirrored reflection

. Cameras with automatic focus bounce a sonar (sound) beam from the object being photographed, and compute distance from the time interval between sending and receiving the signal. Why will these cameras not focus properly for photographs of mirror images? Sound bounced from mirror, not from image.

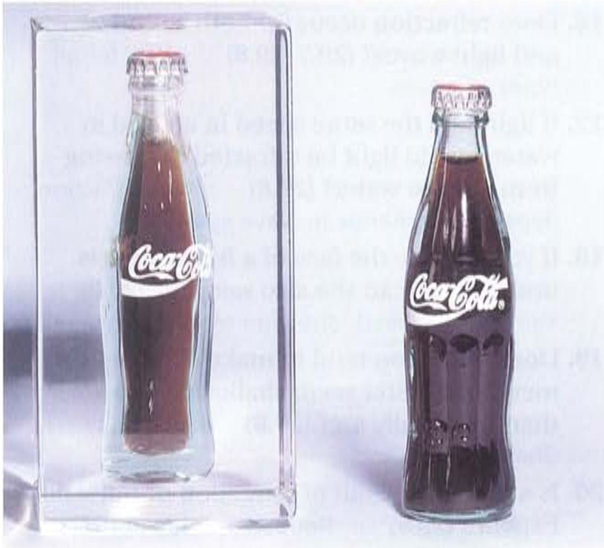
. Why is an echo weaker than the original sound? Sound, like any wave, weakens with distance.

. Does the reflection of a scene in calm water look exactly the same as the scene itself only upside down? (*Hint:* Place a mirror on the floor between you and a table. Do you see the top of the table in the reflected image?) No, reflected view is object seen from lower angle

. If you were spearing a fish with a spear, would you aim above, below, or directly at the observed fish to make a direct hit? Would your answer be the same if you used laser light to "spear" the fish? Defend your answer. Below. Aim *at* for laser, refracts along same path

. A rainbow viewed from an airplane may form a complete circle. Will the shadow of the airplane appear at the center of the circle? Explain with the help of Figure 29.26. Yes, as the sun is directly behind you

10. The photo below shows two identical cola bottles, each with the *same* amount of cola. The right bottle is in air, and the left bottle is encased in solid plastic that has nearly the same "index of refraction" as glass (the speed of light in the plastic and in glass are nearly the same). Which bottle shows an illusion of the amount of cola? How does the other bottle give a truer view of its contents? "Thin" cola more accurate; See Fig. 29.19



Think and Solve

Math reinforcement—variable substitution and equation solving

1. When light strikes glass perpendicularly, about 4% is reflected at each surface. How much light is transmitted through a pane of window glass? About 92%

2. Suppose you walk toward a mirror at 1 m/s. How fast do you and your image approach each other? (The answer is *not* 1 m/s.) 2 m/s

3. A bat flying in a cave emits a sound and receives its echo in one second. How far away is the cave wall? $d = vt = (340\text{ m/s}) \times (0.5\text{ s}) = 170\text{ m}$

4. An oceanic depth-sounding vessel surveys the ocean bottom with ultrasonic sound that travels 1530 m/s in seawater. Find the depth of the water if the time delay of the echo to the ocean floor and back is 6 s. Depth $= vt = (1530\text{ m/s})(3\text{ s}) = 4590\text{ m}$